Total Dose Effects in Conventional Bipolar Transistors

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Introduction

Extensive work has been done on ionizing radiation effects in MOS devices, and great strides have been made in understanding degradation mechanisms as well as in developing hardening techniques for MOS technology. In contrast, little recent work has been done on total dose effects in conventional bipolar transistors.†† Older bipolar work was based on test structures with gated regions over the emitter-base junction, [3-5] which is difficult to extend to production transistors without the special gate regions. Many systems use MilSpec devices without explicit controls on radiation hardness, relying on lot sample test data for hardness assurance. This approach can be effective, but provides no alternative if the radiation hardness of a specific transistor type falls below minimum requirements.

Recent experience on the Cassini spacecraft project has shown that some bipolar devices exhibit large decreases in gain at low total dose levels, severely impacting their use in space. Figure 1 compares gain degradation of two small-signal transistors, measured at the lowest collector current in the manufacturer's specifications. The 2N918 transistor exhibits only small changes in gain with total dose, while the 2N3700 is severely degraded, even at levels below 10 krad(Si). The gain loss is so severe that it is extremely difficult to use this device on the project, which must operate at levels between 50-100 krad(Si). This extreme degradation was not observed for earlier lots from the same manufacturer, and was greater than anticipated for any bipolar transistor with standard construction and normal breakdown voltage requirements.

This paper examines various factors in bipolar device construction and design, and discusses their impact on radiation hardness. The intent of the paper is to improve understanding of the underlying mechanisms for practical devices without special test structures, and to provide (1) guidance in ways to select transistor designs that arc more resistant to radiation damage, and (2) methods to estimate the maximum amount of damage that might be expected from a basic transistor design. The latter factor is extremely important in assessing the risk that future lots of devices will be substantially below design limits, which are usually based on test data for. older devices,

Experimental Approach

Five different types of small-signal NPN transistors were selected for this work that are representative of general-purposc transistors used in typical systems. All were procured from applicable MilSpecs, with special lot identification required by JPL for flight applications. Two operational amplifiers were also tested to provide a comparison between conventional transistors and linear inte.grated circuits. For operational amplifiers, gain of the. input transistors was used for comparison with the discrete transistors. Electrical properties of the transistors are summarized in Table 1.

Irradiations were done with a Shepherd cobalt-60 irradiator, with a nominal dose rate of 65 rad(Si)/s. For transistors, standard bias conditions during irradiation were as follows: 75% of the rated V_{CE} from collector to emitter, and -2 V applied from base to emitter. In addition, a limited number of tests were done at lower collector-emitter and base-emitter voltages to investigate the effect of bias on gain degradation. Operational amplifiers were biased in a unity-gain configuration with power supply voltages of 1 S and -15 V. A lead-aluminum shield surrounded the devices during irradiation to reduce dose enhancement effects. After each irradiation devices were removed from the cell, measuring the gain with an HP4062 parameter measurement system (a benchtop IC tester was used to measure the operational amplifiers). Time between successive irradiations was approximately 20 minutes. After the last irradiation, devices were annealed at room temperature for 24 hours, using the same bias conditions applied during irradiation, and remeasured.

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†† An important exception is recent work on scaled devices with oxide sidewalls.[1,2] Explicit dependence on dose rate has been observed for these devices.

The specification-sheet value of V_{CE} was used for transistor gain measurements (typically 10 V). Measurement accuracy was 1 % or better, as verified with unirradiated control samples. Initial analysis of gain degradation was done using the parameter $\Delta(1/h_{FE}) = 1/h_{FE(rad)} - 1/h_{FE(init)}$, which is often used as a basic parameter to describe total dose degradation. Note, however, that although $\Delta(1/h_{FE})$ may be linear with dose at low total dose levels, it can be either sublinear or superlinear at sufficiently high doses, This has important consequences for applications because of the requirement to determine design margin or shielding requirements, as well as the need to interpolate between different radiation levels and operating currents.

Initial Results

Before discussing mechanisms in more detail, it is useful to examine general features of the degradation that was observed. The sensitivity of the various devices to total dose irradiation varied widely, as shown in Figure 2, which compares A(1 /h_{FE}) at the lowest specified operating current for the five transistors, along with $\Delta(1/h_{FE})$ of input transistors for the two operational amplifiers. The gain degradation varies more than two orders of magnitude. Clearly there are large risks in using devices with higher damage factors except in applications with very low gain requirements, and it is important to understand why such large variations in damage occur for different device types.

A number of factors were examined to see if there were basic correlations between device properties and total dose sensitivity. The most sensitive transistors included a low-current, high-gain linear amplifier, and a general-purpose transistor which operated over a wide range of collector currents, and thus there was no general conflation with operating current. However, a general correlation was observed bet ween Δ(1 /h_{FE}) at low currents and the rated collector-base voltage, as shown in Figure 3 [these results are normalized to 10 krad(Si)]. This suggests that even though the emitter-base junction is the critical region for surface-related darnage, tradeoffs in transistor design related to collector voltage rating directly affect radiation hardness.

Bias Dependence. Radiation tests using different bias voltages were done for some devices. As shown in Figure 4, significantly higher degradation occurred when the device was biased at high voltage during irradiation than for lower voltages (ail measurements were done with $V_{CE} = 10$ V). At low operating current, $\Delta(1/h_{FE})$ is approximately four times higher at 50 V than at 10 V. This result differs from data recently reported for scaled bipolar transistors with integrated sidewalls, for which gain degradation exhibited no dependence on collector voltage during irradiation. [2]

Tests were also done with different emitter-base voltages, Somewhat less degradation was observed when the reverse bias on the emtter-base junction, but the magnitude of the effect varied for different devices. This was partly doe to differences in emitter geometry; details will be provided in the full paper.

Annealing and Dose Rate Effects. All devices were allowed to anneal at room temperature, under bias, for 24 hours after the last radiation level. As expected, some recovery in gain occurred, consistent with results for older devices, Tests of the two op-amps were done at 1 rad(Si)/s to examine dose-rate effects, which have been reported for newer, digital bipolar devices with oxide-isolated sidewalls for dose rates between 1 and 100 rad(Si)/s. Results were nearly identical for tests at 1 and 65 rad(Si)/s, which suggests that the dose-rate effect observed for scaled bipolar technologies is related to oxide sidewalls, as discussed in Reference 2, and will not occur in conventional bipolar structures,

Wafer Lot Dependence. Samples for one of the device types (2 N2920) were obtained from two different wafer lots. Even though both lots were produced by the same manufacturer over a six-month time period, $\Delta(1/h_{FE})$ for the two lots differed by more than a factor of two. Similar differences between manufacturing lots have been reported earlier. [6] Additional information on wafer lot dependence will bc provided in the full paper.

Discussion

One important difference between MOS and bipolar devices is the relationship between ionizing radiation effects and geometry. For MOSFETs, threshold voltage (and its two components) are generally independent of geometry (except for highly scaled devices). This self-scaling feature makes it much easier to interpret ionizing radiation effects in MOS devices. Simply knowing the oxide thickness allows onc to place limits on the degradation that can occur in these devices.[7] The situation is far more complicated for bipolar devices. Although oxide thickness and proper-tics are still important, emitter-base geometry is directly involved in ionizing radiation effects in bipolar devices. The perimeter-area ratio is a key factor in determining total dose sensitivity, [3] and all things being equal, predicts that as devices are scaled to smaller dimensions, they should be more sensitive to ionizing radiation. Furthermore, many variations occur in specific transistor designs; in some cases metal conductors pass directly over regions of the emitter-

base junction, increasing the electric field in localized regions. As shown in Table 1, three of the transistors in this study had overlapping metal designs. One device used a waffle-like structure, with extensive metal overlap. Note further that devices of the same generic type from different manufacturers may use different emitter geometries. This was observed for two different manufacturers of the 2N2222, and further complicates interpretation of test data, particularly if there are differences in the periphery of the emitter over which there is overlapping gate metallization.

Even though transistor geometry is important, it was not the dominant factor in determining relative degradation between the different device types in this study. Figure 5 shows the perimeter-area ratio for the five transistors, along with the input transistors of the two operational amplifiers; the line shows the P/A ratio for a square emitter. The 2N918 has the highest P/A ratio, but as shown in Figure 1, it is the device with the lowest radiation sensitivity. Operating current densities were found to vary over a wide range for tbe different transistor types, as shown in Figure 6. Here the 2N918 stands out; clearly it has the highest current density of any of the devices at both ends of its specified operating range and this is one of the major reasons for its improved hardness.

Clearly breakdown voltage has a pronounced effect on collector doping, However, two additional factors affect the choice of collector doping and base width, which are interrelated, The first is the Kirk effect, [8] which causes the base region to extend into the collector. This restricts the current density for lightly doped collectors. The second factor is the Early effect, [9] which forces tradeoffs in base doping profile and base width. These factors are the main reasons that the 2N3501 and 2N3700 have increased sensitivity to radiation, Additional details will be provided in the full paper, along with analysis of the Gummel number for the various device types.

Summary and Conclusions

This paper has discussed basic relationships between total dose degradation in conventional bipolar transistors and transistor design. A general correlation was found between gain degradation and collector-base breakdown voltage rating, which appears to be related to transistor design constraints imposed by the Kirk effect, as well as the need to control voltage dependence of gain (Early effect). These factors limit the maximum current density and also impose wider base width, Emitter geometry is also important in determining total dose effects in bipolar devices, and can be widely different for different transistor types as well as for transistors of the same generic type from different manufacturers. Some emitter designs have extensive regions where base metallization passes over the emitter-base region, increasing the importance of emitter-base bias on total dose damage.

Linear integrated circuits appear to be somewhat more resistant to radiation damage than discrete transistors. This is due to two factors: lower collector voltage requirements, and the freedom to design devices for a specific application. Investigation of annealing and dose-rate effects for discrete transistors and two operational amplifiers has shown no evidence for the dose-rate dependence that has recently been reported for scaled digital bipolar devices with oxide sidewalls.

References

1. R. L. Pease, et al., "Total Dose Effects in Recessed Oxide Digital Bipolar Microcircuits," IEEE Trans. Nucl. Sci., NS-30, 4216 (1983).

2. R. N. Nowlin, et al., "Trends in the Total-Dose Response of Modern Bipolar Transistors," IEEE Trans. Nucl. Sci., NS-39, 2026 (1992).

3. E. H. Snow, A. S. Grove, and D. J. Fitzgerald, "Effects of ionizing Radiation on Oxidized Silicon Surfaces and Planar Devices," Proc. IEEE, 55, No. 7,1168, 1967.

4. M. W. Hillen and J. Holsbrink, "The Base Current Recombining at the Oxidized Silicon Surface," Solid-State Elect., 26, No. 5, 453 (1982).

5. A. R. Hart, et al., "Hardness Assurance Considerations for Long-Term Ionizing Radiation Effects on Bipolar Structures," IEEE Trans. Nucl. Sci., NS-25, 1502 (1978).

6. 1. Arimura and A. I. Namenson, "Hardness Assurance Statistical Methodology for Semiconductor Devices," IEEE Trans. Nucl. Sci., NS-30, 4322 (1983).

7. J. M. McGarrity, "Considerations for Hardening MOS Devices and Circuits for Low Radiation Doses," IEEE Trans. Nucl. Sci., NS-27, 1739 (1980).

8. C. T. Kirk, "A Theory of Transistor Cutoff Frequency (fT) Fall-Off at High Current Density," IEEE Trans. Elect. Dev., ED-9, 164 (1962).

9. F. D. Malone, "The Early Voltage of a Bipolar Transistor," IEEE Trans. Elect. Dev., 167, February, 1977.

Table 1. Properties of Transistors Included in the Study

Device	Rated BVcb (V)	Emitter Design	Base Metal Coverage	Emitter Area $(\mu m)^2$	Perimeter (μm)
2N918	30	Stripe	10%	605	121
2N2222A	75	Interdigitated	None	28,000	1635
2N2920	60	Ring/dot	4.3%	3,830	220
2 N 3 5 0 1	150	Waffle	36%	90,900	4720
2N3700	140	Interdigitated	None	82,600	3160
LM101	30	Ring/dot	None	8.170	320
LM108	5	Ring/dot	None	4.580	240

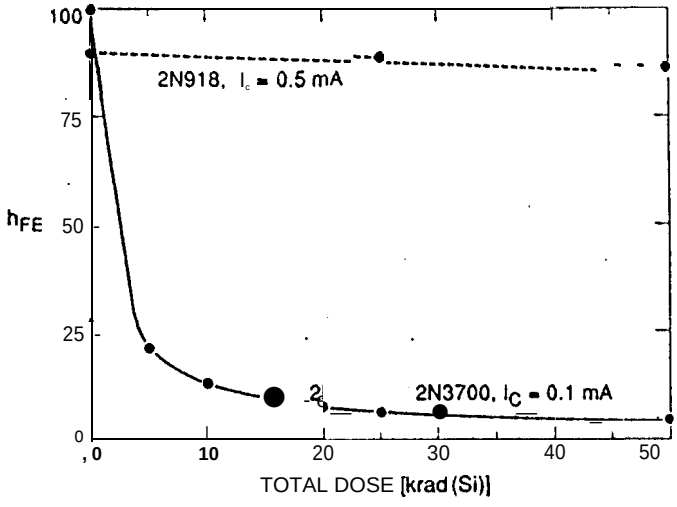

Figure 1. Degradation of two types of small-signal transistors showing extreme ranges in total dose sensitivity,

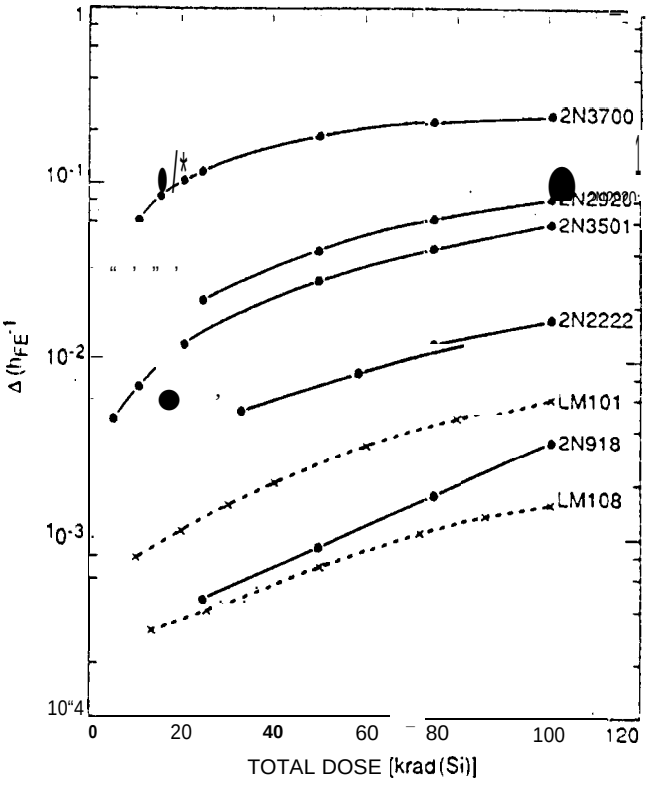

Figure 2. Change in $\Delta(1/h_{FE})$ at low currents for the various device types

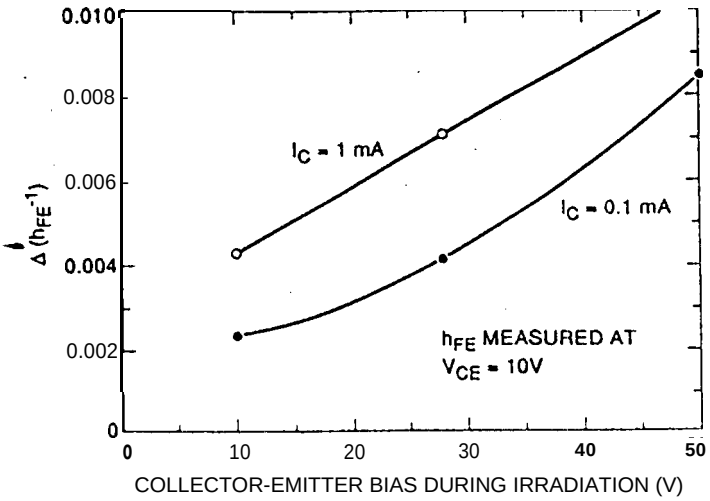

Figure 3. Correlation between $\Delta(1/h_{FE})$ and rated collector-base breakdown.

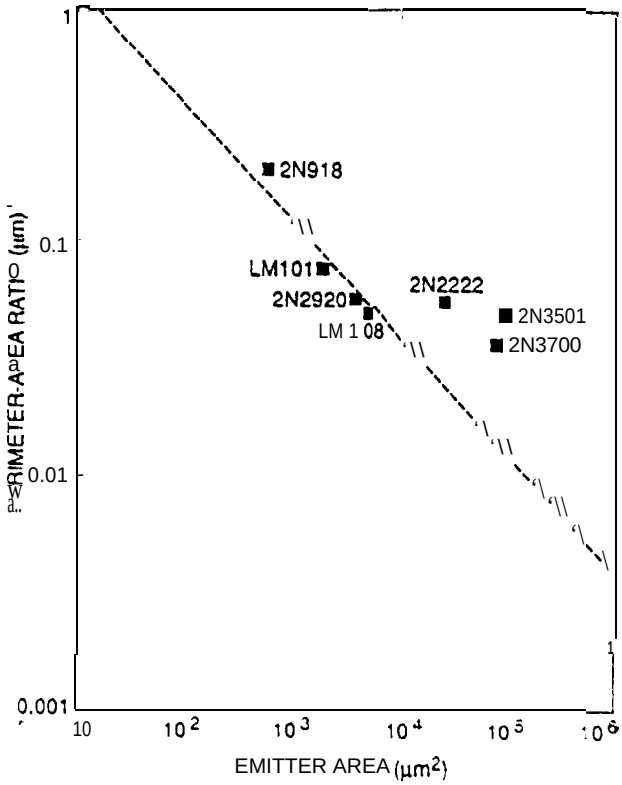

Figure 5. Perimeter/area ratio for the various devices.

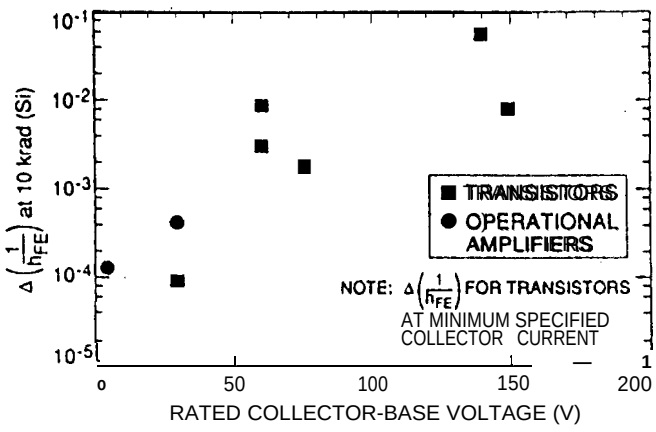

Figure 4. Effect of collector-emitter bias on degradation (2N222 transistor)

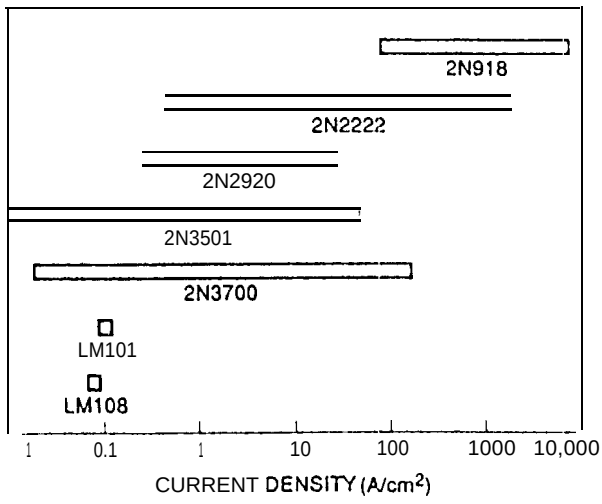

Figure 6. Operating current densities for the various devices.